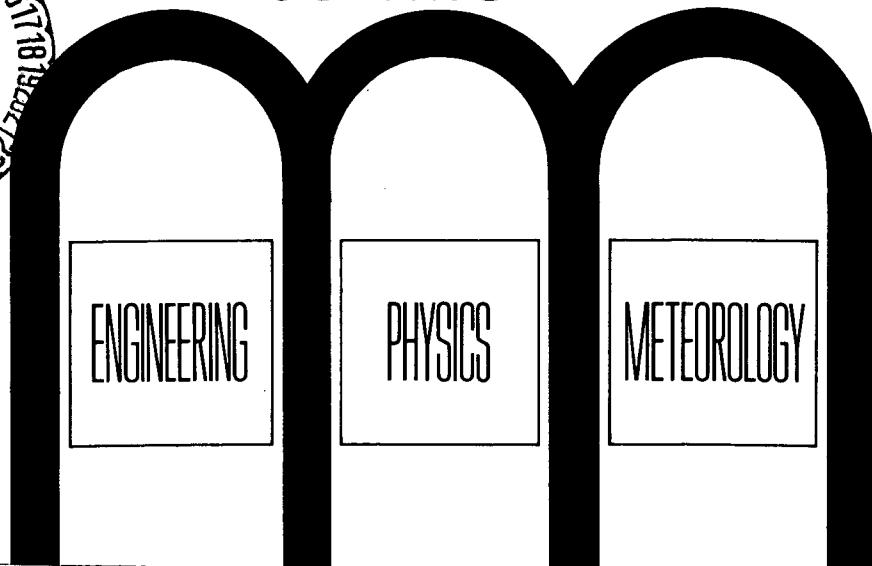


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Cross-Field Current-Driven  
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P.J. Barrett,\* B.D. Fried, C.F. Kennel,  
J.M. Sellen, and R.J. Taylor\*\*

Department of Physics, University of California,  
Los Angeles, California 90024

and

TRW Systems, Redondo Beach,  
California 90278

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\* Present address: Culham Laboratory, Abingdon, Berkshire, England.

\*\* Present address: Physics Department, Massachusetts Institute of Technology,  
Cambridge, Mass. 02139.

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Cross-Field Current-Driven Ion Acoustic Instability<sup>†</sup>

P. J. Barrett,<sup>\*</sup> B. D. Fried, C. F. Kennel, J. M. Sellen, and R. J. Taylor<sup>\*\*</sup>

Department of Physics, University of California, Los Angeles, California 90024

and

TRW Systems, Redondo Beach, California 90278

Abstract

This instability occurs when electrons and ions have a relative streaming velocity, along  $x$ ,  $v_D > c_s = (T_e/M)^{1/2}$ , across a weak magnetic field,  $B_z$ . If  $k_x r_{ci} \gg 1$  and  $\omega \ll \omega_{ce}$ , the spatial growth rate is enhanced by a factor  $k_x/k_z$  over the value at  $B_z = 0$ . Measurements of growth rate ( $\text{Im } k/\text{Re } k$ ) have been carried out in two different plasma configurations as a function of both  $B_z$  and  $\omega$ . The results are consistent with the linear dispersion relation for this instability.

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<sup>\*</sup> Present address: Culham Laboratory, Abingdon, Berkshire, England.

<sup>\*\*</sup> Present address: Physics Department, Massachusetts Institute of Technology, Cambridge, Mass.

The theory of cross-field instabilities, i.e., those associated with the relative streaming of electrons and ions across a magnetic field, has been examined recently by several authors.<sup>1-7)</sup> We report here two direct and distinct experimental observations of one class of such instabilities, namely ion acoustic waves propagating at large angles to the magnetic field  $B_z$  [i.e., with  $l \gg k_z/k_x > (m/M)^{1/2}$ ] at frequencies well below the electron cyclotron frequency,  $\omega_{ce}$ ; wavelengths of the order of the electron gyroradius,  $r_e$ ; and phase velocity close to the ion drift velocity,  $v_D$ . Since both of the experiments discussed here satisfy  $r_e \ll L \ll v_D/\omega_{ci}$ , where  $L$  denotes the dimensions of the plasma, the conditions generally assumed in calculations on these cross-field instabilities, namely, magnetized electrons but straight-line ion motion, are well satisfied.

This instability differs from the ion acoustic instability with  $B = 0$  (or  $k \parallel B$ ) in the following respect: over the wide range of drift velocity between the ion acoustic velocity  $c_s = (T_e/M)^{1/2}$  and the electron thermal speed,  $a_e = (2T_e/m)^{1/2}$ , the maximum growth rate is enhanced by a factor  $k/k_z$  because the electron motion along  $B_z$ , when projected onto the direction of the wave number  $k$ , corresponds to a reduced thermal velocity  $\bar{a}_e = (k_z/k)a_e$  insofar as wave-particle resonance is concerned. Thus, for  $kr_e < 1$  and  $\omega < \omega_{ce}$ , the wave phase velocity can coincide with the velocity of maximum slope of the averaged electron distribution function,  $\langle k \cdot \partial f / \partial v \rangle / k$ , even when  $v_D/a_e \ll 1$ , thus enhancing the growth rate, which is proportional to this slope.

A further consequence of the magnetic constraint on the electron motion is that this instability, like the electron cyclotron drift instability at  $\omega \geq \omega_{ce}$ ,<sup>4)</sup> is relatively insensitive to  $T_e/T_i$ . For example, whereas the threshold value of  $v_D$  for growth rises from  $c_s$  to  $a_e$  as  $T_i/T_e$  varies from 0

to 1 in the  $B = 0$  case, the threshold remains of the order of  $c_s$  when  $B \neq 0$ , provided that  $k_z/k$  can be small as  $(m/M)^{1/2}$ . Well above the threshold, i.e., for  $c_s \ll v_D \ll a_e$ , the instability can have an appreciable growth rate for larger  $k_z/k$  [ $\sim (m/M)^{1/2}(v_D/c_s)$ ], even when  $T_i/T_e \sim 1$ .

The dispersion relation for cross-field electrostatic waves in a homogeneous plasma, with an isotropic Maxwellian electron distribution (in the lab frame) and ions streaming with  $v_D$  oblique to  $B$ , is<sup>1)</sup>

$$1 + k^2/k_D^2 + (\omega/k_z a_e) \sum_{n=-\infty}^{\infty} \Gamma_n Z_n - (T_e/2T_i) Z'(\bar{\omega}/ka_i) = 0 , \quad (1)$$

where  $k_D = (4\pi n e^2/T_e)^{1/2}$ ;  $\bar{\omega} = \omega - k_z v_D$  is the frequency in the ion rest frame;  $\Gamma_n = e^{-b} I_n(b)$ , with  $b = \frac{1}{2} (k_x r_e)^2$ ,  $I_n$  being the modified Bessel function; and  $Z_n = Z[(\omega - n\omega_{ce})/k_z c_e]$ ,  $Z$  being the plasma dispersion function.<sup>8)</sup> In the limit  $k_z \rightarrow 0$ , Eq. (1) reduces to the dispersion relation studied by Forslund, et al.<sup>4)</sup> in the high frequency regime ( $\omega \geq \omega_{ce}$ ). Here we consider instead the case  $\omega < \omega_{ce}$ ; then  $Z_n \approx -Z_{-n}$  and the sum in (1) reduces to the single term  $\Gamma_0 Z_0$ , giving a dispersion relation (also obtained by Aref'ev<sup>1)</sup>),

$$2\kappa \equiv 2[1 - \Gamma_0 + k^2/k_D^2]/\Gamma_0 = Z'(\omega/k_z a_e) + (T_e/T_i \Gamma_0) Z'(\bar{\omega}/ka_i) , \quad (2)$$

which is similar to that for ion acoustic waves with  $B = 0$ . The only differences are the factor  $\Gamma_0$  in the ion term; the replacement of the usual  $k^2/k_D^2$  by  $\kappa$  (which reduces to  $k^2/k_D^2$  for  $k_x r_e \ll 1$ ); and, most important, the replacement of  $\omega/ka_e$  in the electron  $Z$  function by  $\omega/k_z a_e$ , which leads to the aforementioned  $k/k_z$  enhancement of the growth rate. In the cold fluid limit ( $T_e, T_i \rightarrow 0$ ) both  $Z'$  functions may be approximated by their asymptotic forms, whereupon (2) reduces to the dispersion relation of Ashby and Paton,<sup>6)</sup> which has a structure similar to that for the usual two beam instability. However, for the regime studied here, the argument  $\omega/k_z c_e$  is not large<sup>9)</sup> and so a power

series expansion for the electron Z' function is more appropriate than the asymptotic expansion. If  $T_e/T_i$  is large, we can continue to use the asymptotic form for the ion Z' function. If we also assume  $|\omega/k_z a_e| \ll 1$ , then we obtain a simple, explicit expression for the spatial growth rate,

$$k_i/k_r = (\text{Im } k/\text{Re } k) = (\pi m/8M)^{1/2} (k_r/k_z) (1 + k_r^2/k_D^2)^{-3/2} \Gamma_0 . \quad (3)$$

This equation shows the dependence of growth rate on  $B$  (through  $\Gamma_0$ ) and it clearly exhibits the  $(k/k_z)$  enhancement. [While it predicts a continued increase of  $k_i/k_r$  with  $k/k_z$ , use of the correct electron Z' function in (2) shows that the maximum  $k_i/k_r$  occurs for  $|\omega/k_z a_e|$  of order 1.]

For comparisons with experiment, we have used (2) to calculate  $k_i/k_r$  for measured values of  $b$ ,  $k/k_D$  and  $v_D/c_s$ . ( $T_i/T_e$  is typically  $\sim 0.1$ , justifying use of the asymptotic form of the ion Z' function.) The choice of  $k/k_z$ , however, presents a problem. If  $k_z$  is assumed to be of order  $(\pi/L)$ , where  $L$  is the plasma length along  $B$ , then the calculated growth rates agree closely with those observed experimentally only for large values of  $b$ . Attempts either to measure or prescribe  $k_z$  for small  $b$  show that the instability runs at  $k_z$  values which are smaller than  $(\pi/L)$ . Presumably, the wave electric fields fall rapidly to zero in the sheaths at the plasma boundaries, but have long wavelengths, greater than  $2L$ , along the magnetic field in the bulk of the plasma. Since accurate measurements of  $k_z$  have proven difficult, we treat the dimensionless quantity

$$s \equiv (k/k_z) (m/2M)^{1/2} \quad (4)$$

as a free parameter. Choosing  $s$  to maximize the growth rate for fixed values of the other parameters gives reasonable agreement with experimental results for large  $b$ , but the measured growth rate falls below the optimum value for small  $b$  (cf. Figs. 2 and 3). This is true whether we vary  $b$  by holding  $k$

constant and varying  $B_z$  ( $b \propto B_z^{-2}$ ) or holding  $B_z$  constant and varying  $k$  ( $b \propto k^2$ ). In the former case we can fit the data very well by allowing  $s$  to vary linearly with  $b^{-1}$ , but we have no physical argument to justify this.

The instability has been directly observed in two quite different plasma configurations. Figure 1(a) shows a Double Plasma (DP) device<sup>10,11)</sup> in which two steady-state argon plasmas ( $n \approx 10^8 \text{ cm}^{-3}$ ), separated by a fine, negatively-biased grid of diameter 27 cm, can be held at independent plasma potentials. An ion beam of this diameter can thus be extracted from the left-hand plasma into the larger right-hand plasma (diameter 40 cm), and velocity-modulated by adding a sinusoidal signal (typically a few mV, i.e.,  $< 10^{-2} T_e$ ) to the left-hand chamber potential. For most of the measurements the separating grid was plane, but, in an attempt to impose a fixed value of  $k_z$ , a corrugated grid such as that shown in Fig. 1(a) was also used. The ion beam is neutralized by electrons from grounded filaments in the right-hand chamber. A large, clean coarse grid, also grounded (i.e., positive with respect to the plasma), helps to make  $T_e$  uniform and also reduces its value by removing more of the faster electrons; the presence of this grid is important since a variation in  $T_e$  of 30%, for example, can change the growth rate by a factor 2. The value of  $k_x$  is determined by the modulation frequency,  $k_x = \omega(v_D - c_s)^{-1}$ . The excited waves are detected by a conventional interferometer system.

Typical spatial growth rates obtained with the DP machine are presented in Fig. 2 as a function of magnetic field for fixed  $k$  ( $f = 1 \text{ MHz}$ ) and varying  $B_z$ . (The dimensionless variable  $b^{-1} \propto B_z^2$  is used as abscissa.) The experimental points are taken from interferometer wave forms. Theoretical curves were obtained by i) choosing the optimum value of  $s$ ; ii) choosing  $s = 0.157$ , corresponding to  $k_z = (\pi/L)$ , where  $L = 50 \text{ cm}$  is, deliberately, chosen to be

somewhat larger than the probable maximum plasma diameter (40 cm); iii) allowing  $s$  to vary linearly with  $b^{-1}$  ( $s = 0.2275 - 0.0275/b$ ). Even with this large value of  $L$ , the experimental data are not consistent with the choice  $k_z = \pi/L$ ; for smaller  $L$ , the agreement is poorer. It appears that, at least for large  $b$ , the instability "chooses" the  $k_z$  value which gives the largest growth. Similar experimental results were obtained over a range of parameters:

$$f = 0.2-1 \text{ MHz}; W = 10-80 \text{ eV}; B_z \leq 40 \text{ g}.$$

A larger plasma, with different boundary conditions and larger  $v_D/c_s$ , is created in the cesium plasma device<sup>12)</sup> shown in Fig. 1(b). Here an ion beam, formed by contact ionization of cesium atoms in a hot porous tungsten plug, is accelerated by a nearby plane tungsten grid and neutralized by electrons from a hot wire. Typically the beam energy is  $\sim 300$  eV ( $v_D \sim 2 \times 10^6 \text{ cm/sec}$ ) and the density at the source is  $\sim 4 \times 10^9 \text{ cm}^{-3}$ , diminishing to  $\sim 10^7 \text{ cm}^{-3}$  two meters downstream, due to beam divergence. The collector plate at the far end is biased negatively to collect the beam ions, while the magnetized electrons form a stationary background fluid which rapidly fills the plasma volume when the beam is switched on.

Data obtained with this configuration are illustrated in Fig. 3, which shows the variation of growth rate with  $k$  (i.e., frequency) for fixed  $B_z = 3 \text{ g}$ ; again,  $b^{-1} \propto k^{-2}$  is used as abscissa. These data come from measurements of the growth of naturally occurring noise, convected with the streaming cesium plasma. Tuned filters isolate particular values of  $\omega = kv_D$ . Just as for fixed  $B_z$  (Fig. 2), the growth rate is close to the maximum value predicted by the dispersion relation for large  $b$ , falling off from that as  $b$  decreases. Choosing  $k = \pi/L$  for realistic  $L$  gives growth rates much smaller than those observed experimentally. A better, but still poor, fit is obtained by choosing

s to be constant, as would be the case if  $k/k_z$  were limited by the lack of magnetic field homogeneity. For example, at an intermediate frequency of 0.6 MHz, the value  $s = 0.45$  shown in Fig. 3 corresponds to  $k/k_z = 2 fL/v_D = 31.6$ , hence to  $L \approx 50$  cm, which is the maximum diameter of the diverging plasma stream. Actually, in the region where growth is observed (about 1m from the plasma source) the diameter is only 25 cm.

The following effects have also been noted: (1) In the DP experiment we attempted to impose a comparatively large  $k_z$  on the wave by segmenting the grid as in Fig. 1(a). In this case the waveform obtained with the probe facing an F (far) segment is initially out of phase with that obtained opposite an N (near) segment and no growth is observed; but at  $x \approx 20$  cm a sharp transition occurs, in which the F and N waves phase-lock and begin to grow rapidly. Apparently the initially dominant  $k_z$  imposed by the grid is swamped by a fast-growing mode corresponding to the minimum  $k_z$  allowed by boundary conditions, magnetic field non-uniformity, etc. The instability is insensitive to small changes in the direction of the magnetic field (up to about 10 degrees). (2) A reduction of the growth rate is observed in both devices when a high frequency modulation signal is applied to the beam, thereby effectively increasing the beam temperature and, hence, the ion Landau damping. For example, a growth rate of  $k_i/k_r = 0.05$  was reduced to zero in the DP device by increasing the energy width of a 45 eV beam from 2.5 to 3.1 eV. (3) At higher  $B_z$ , both plasmas show increased turbulence and a corresponding increase in  $T_e$ .

In summary, we find that in two separate experiments, using quite disparate configurations, the dominant cross-field instability appears to be this low frequency, ion acoustic mode, rather than the high frequency ( $\omega \geq \omega_{ce}$ ) modes predicted in the geometrically more constrained  $k_z = 0$  case. The

comparison of experimental growth rates with those predicted from the dispersion relations indicates that the observed instability at a given  $k_x$  is the fastest growing mode, or one close to it, even though the corresponding  $k_z$  value may be less than  $(\pi/L)$ . So far, direct measurements of  $k_z$  have not been possible. In view of the low threshold ( $v_D \ll a_e$ ) and relative insensitivity to  $T_e/T_i$ , this cross-field ion acoustic instability may be responsible for anomalous transport and ion heating in collisionless shocks,<sup>7)</sup> neutral sheet phenomena (e.g., the Earth's magnetic tail), and other situations where drifts, diamagnetic effects, or similar mechanisms create a relative drift of electrons relative to ions across the magnetic field.

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References and Footnotes

1. V. I. Aref'ev, Soviet Phys.-Tech. Phys. 14, 1487 (1970).
2. H. V. Wong, Phys. Fluids 13, 757 (1970).
3. S. P. Gary and J. J. Sanderson, J. Plasma Phys. 4, 739 (1970);  
S. P. Gary, J. Plasma Phys. 4, 753 (1970).
4. D. W. Forslund, R. L. Morse, and C. W. Nielson, Phys. Rev. Letters 25, 1266 (1970).
5. M. Lampe, W. Manheimer, J. B. McBride, J. H. Orens, R. Shanny, and R. N. Sudan, Phys. Rev. Letters 26, 1221 (1971).
6. D. E. T. F. Ashby and A. Paton, Plasma Phys. 9, 359 (1967).
7. N. A. Krall and P. C. Liewer, Phys. Rev. 4, 2094 (1971).
8. B. D. Fried and S. Conte, The Plasma Dispersion Function (Academic Press, New York, 1961).
9. Specifically, we note that  $\omega/kc_s$  is close to 1. Then  $\omega/k_z a_e^{\tilde{\omega}}$   
 $(k/k_z)(v_D - c_s)/a_e = (k/k_z)(m/2M)^{1/2}(1 - v_D/c_s)$ , which is large only for propagation very nearly perpendicular to  $\tilde{k}$ . For modest values of  $v_D/c_s$  and for most orientations of  $\tilde{k}$ , this quantity will actually be small.
10. R. J. Taylor and K. R. Mackenzie, in Proceedings of the International Conference on Physics of Quiescent Plasmas (Ecole Polytechnique, Paris, 1969), Pt. 3, p. 57; R. J. Taylor, D. R. Baker, and H. Ikezi, Phys. Rev. Letters 24, 205 (1970).
11. R. J. Taylor, Ph.D. thesis, U.C.L.A. (1970).
12. J. M. Sellen, W. Berstein, and R. F. Kemp, Rev. Sci. Instr. 36, 316 (1965).

Figure Captions

Fig. 1. (a) Double-Plasma Apparatus. (b) Streaming Cesium Plasma Device.

Fig. 2. Experimental and theoretical growth rate  $k_i/k_r$  versus  $b^{-1}(B_z) = (e^2/mT_e k_x^2)B_z^2$  for waves excited in Double-Plasma Device, with  $f = 1$  MHz, beam energy  $W = 80$  eV,  $n = 10^8 \text{ cm}^{-3}$ . The "optimum s" theoretical curve results from varying  $s = (k/k_z)(m/2M)^{1/2}$  to maximize  $k_i/k_r$ , all other parameters being held constant. The choice  $s = 0.157$  corresponds to choosing  $k_z = (\pi/50) \text{ cm}^{-1}$ . A good fit to the data is obtained with  $s = 0.2275 - 0.0275 b^{-1}$ .

Fig. 3. Experimental and theoretical growth rate  $k_i/k_r$  vs.  $b^{-1}(k_x) = (e^2 R_z^2/m T_e)^{1/2} k_x^{-2}$  for plasma noise observed in the central region of the streaming Cesium Plasma Device,  $0.2 \text{ MHz} \leq f \leq 0.8 \text{ MHz}$ . Density  $n \approx 2 \times 10^8 \text{ cm}^{-3}$ , ion velocity  $v_D = 2 \times 10^6 \text{ cm/sec}$ . The choice  $s = 0.045$  corresponds to a constant value  $k/k_z = 2fL/v_D = 31.6$ .

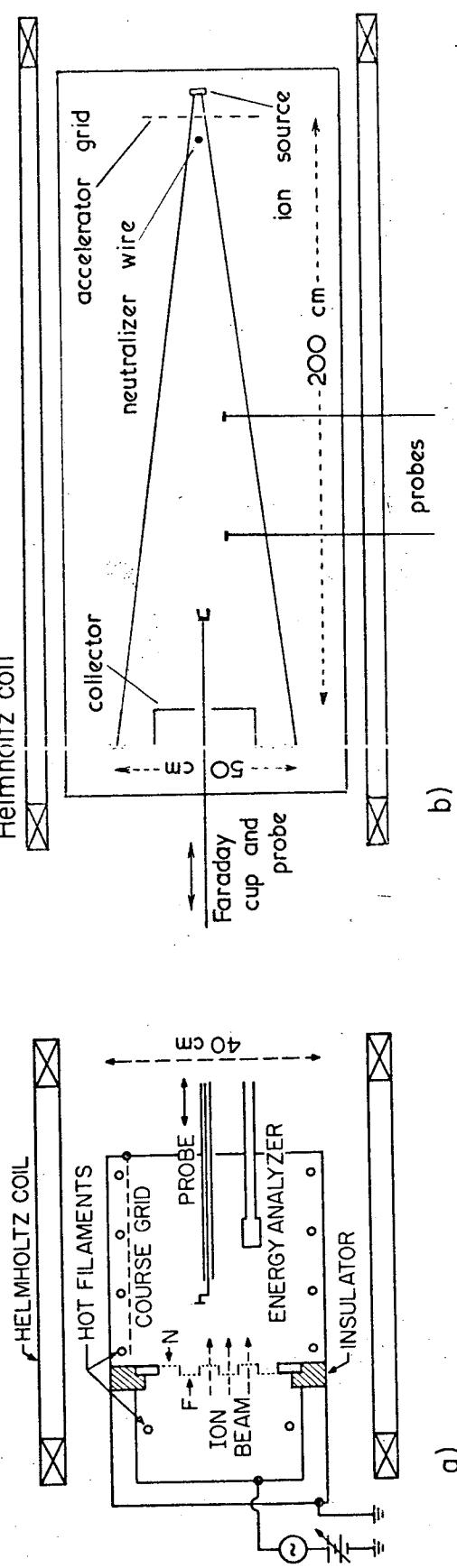


Figure 1 (a) Double-Plasma Apparatus. (b) Streaming Cesium Plasma Device.

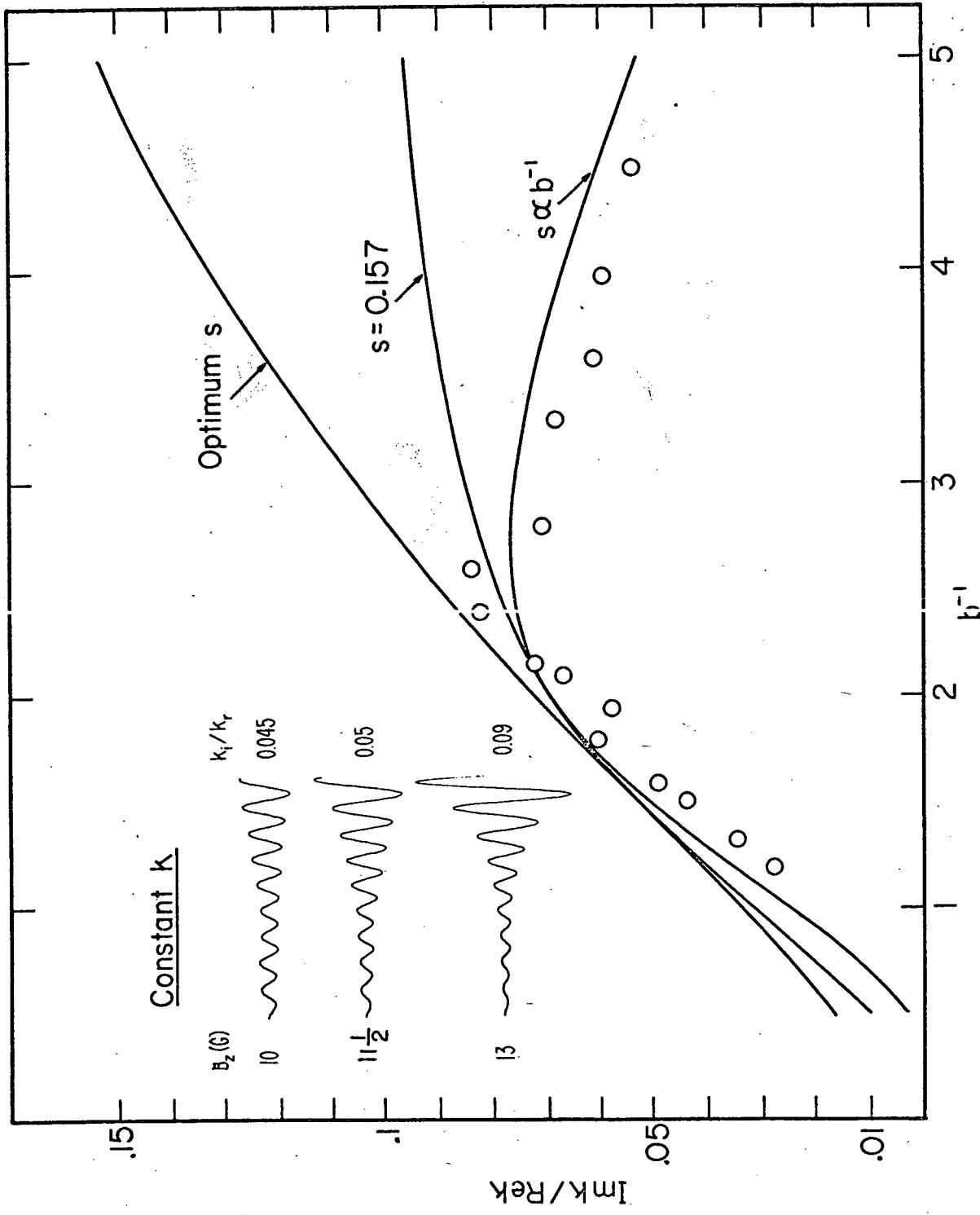


Figure 2 Experimental and theoretical growth rate  $k_i/k_r$  versus  $b^{-1}(B_z)^2$  for waves excited in Double-Plasma Device, with  $f = 1$  MHz, beam energy  $W = 80$  eV,  $n = 10^{-6}$  cm $^{-3}$ . The "optimum  $s$ " theoretical curve results from varying  $s = (k/k_z)(m/2N)^{1/2}$  to maximize  $k_i/k_r$ , all other parameters being held constant. The choice  $s = 0.157$  corresponds to choosing  $k_z = (\pi/50)$  cm $^{-1}$ . A good fit to the data is obtained with  $s = .2275 - .0275 b^{-1}$ . [Inset shows interferometer waveforms at  $f = 0.5$  MHz and beam energy,  $\omega_b$ .]

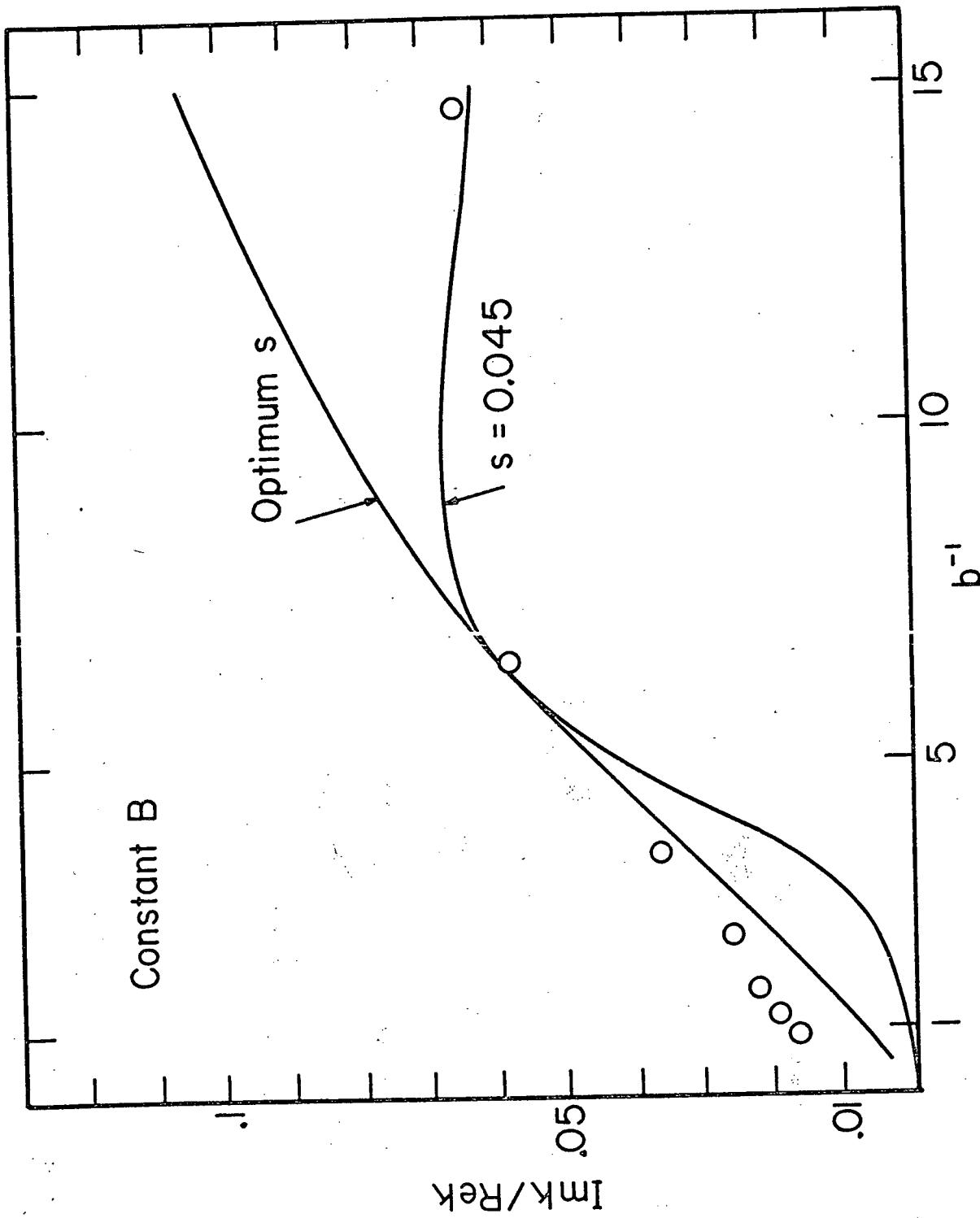


Figure 3 Experimental and theoretical growth rate  $k_i/k_r \propto b^{-1}(k_x) = (e^2 B_z^2/m T_e) k^{-2}$  for plasma noise observed in the central region of the streaming Cesium Plasma Device,  $0.2 \text{ MHz} < f < 0.8 \text{ MHz}$ . Density  $n \approx 2 \times 10^{16} \text{ cm}^{-3}$ , ion velocity  $V_D = 2 \times 10^6 \text{ cm/sec}$ . The choice  $s = .045$  corresponds to a constant value  $k/k_z = 2fL/v_{pi} = 31.6$ .

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